Contrasting the effects of the 1850-1975 increase in sulphate aerosols from North America and Europe on the Atlantic in the CESM model

Citation for published version:
Undorf, S, Bollasina, MA, Booth, BBB & Hegerl, GC 2018, 'Contrasting the effects of the 1850-1975 increase in sulphate aerosols from North America and Europe on the Atlantic in the CESM model', *Geophysical Research Letters*, vol. 45, no. 21, pp. 11,930-11,940. https://doi.org/10.1029/2018GL079970

Digital Object Identifier (DOI):
10.1029/2018GL079970

Published In:
Geophysical Research Letters

Contrasting the effects of the 1850-1975 increase in sulphate aerosols from North America and Europe on the Atlantic in the CESM model

S. Undorf[1], M. A. Bollasina[1], B. B. B. Booth[2], and G. C. Hegerl[1]

Sabine Undorf, S.Undorf@ed.ac.uk

[1]School of GeoSciences, The University of Edinburgh, The King's Buildings, Alexander Crum Brown Road, Edinburgh EH9 3FF, UK.

[2]Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2018GL079970

The extent and mechanisms of the Atlantic response to the historical (1850-1975) increase of sulphate aerosol emissions from North America (NA) and Europe (EU) as simulated in 8-member ensemble experiments with the coupled Community Earth System model (CESM1-CAM5) are contrasted. The results show that aerosols from either source cause a long-term cooling of North Atlantic sea-surface temperatures (SSTs), with the patterns a combination of atmospheric aerosol effects and an aerosol-induced strengthening of the Atlantic Meridional Overturning Circulation (AMOC). The response to NA emissions is larger since prevailing winds cause wider aerosol spread over the Atlantic, collocated with climatological cloud cover. The Inter-Tropical Convergence Zone shifts southward affecting tropical precipitation globally. The simulated (multi)decadal components of SST and AMOC variability are furthermore primarily externally forced. The analysis provides novel insights into the mechanisms of aerosol impact on the Atlantic. It suggests that projected further emission reductions will lead to opposite changes.

1. Introduction

Low-frequency variations of sea surface temperature (SST) in the North Atlantic, commonly referred to as Atlantic Multidecadal Variability (AMV), have a significant impact on regional and global climate [*Christensen et al.*, 2013] due to their basin-wide spatial scale and persistence. These include, for example, links with changes of Sahel rainfall [*Knight et al.*, 2006; *Ting et al.*, 2011], North and South American hydroclimate [*Nigam et al.*, 2011; *Kavvada et al.*, 2013], and Atlantic Hurricane frequency [*Zhang and Delworth*, 2006; *Dunstone et al.*, 2013]. Identifying the mechanisms behind North Atlantic SST variations is both crucial to provide reliable decadal predictions [*Smith et al.*, 2010; *Steinman et al.*, 2015] and to assess future projections of ocean circulation feedbacks [*Rahmstorf et al.*, 2015; *Swingedouw*, 2015].

On the factors driving North Atlantic variability, however, substantial research in the last decade has brought more controversy than consensus. A key issue are the roles of internal variability vs. external forcing during the historical period [*Knight*, 2009; *Ting et al.*, 2009, 2014], and the extent of their interaction [*Tandon and Kushner*, 2015]. A dominant role for external forcing, especially from volcanic eruptions, has for instance been concluded from models, observations, and last millennium proxies [e.g., *Otterå et al.*, 2010; *Knudsen et al.*, 2014; *Wang et al.*, 2017; *Bellomo et al.*, 2017], but the assessment is complicated by the short observational record and the complex spatio-temporal nature of North Atlantic SST variability, making findings controversial.

Another side of the debate are the relative roles of the ocean and the atmosphere – while a number of studies have emphasized the role of the ocean circulation as the key driver of the AMV via density fluctuations associated with the Atlantic Meridional Overturning Circulation (AMOC) [*Delworth et al.*, 1993; *Knight et al.*, 2005; *Marini and Frankignoul*, 2014; *Zhang et al.*, 2016; *Zhang*, 2017], other studies have proposed changes in atmospheric circulation, including stochastic forcing [*Clement et al.*, 2015, 2016] or variability of the North Atlantic Oscillation (NAO) [*Gulev et al.*, 2013], to drive North Atlantic SST variations through air-sea interactions, or both on different time scales [*Bjerknes*, 1964]. An important contribution from the AMOC and/or the NAO [*Delworth et al.*, 2017], however, does not necessarily exclude a key role for external forcing, since they might themselves be impacted by forcing [*Stenchikov et al.*, 2009; *Ding et al.*, 2014]. *Tandon and Kushner* [2015], for instance, showed that a forced and an unforced component of the AMV [also *Ba et al.*, 2014] coexist in a range of CMIP5 models.

The role of anthropogenic aerosols, and sulphate in particular, in modulating North Atlantic SST variability during the twentieth century are especially debated. *Booth et al.* [2012] argued that the AMV during the instrumental period was primarily driven by aerosols, with an imprint also on Atlantic atmospheric variability [*Dunstone et al.*, 2013]. However, *Zhang et al.* [2013] subsequently pointed out discrepancies in the simulated subsurface fields and ocean circulation, questioning the realism of the aerosol dominance inferred from the model. More recently, however, most of the SST variance over the Atlantic was found to be radiatively forced also in other models [*Bellomo et al.*, 2017; *Murphy et al.*, 2017], with a distinct contribution of anthropogenic aerosols on both temporal and spatial variability. Note that aerosol impact on SSTs elsewhere, possibly including decadal ENSO variability, has also been suggested [e.g., *Sutton and Hodson*, 2007; *Westervelt et al.*, 2018].

In addition to the studies focussing on the AMV, others found a longer-term impact of anthropogenic aerosols on downward surface solar radiation over the Atlantic and consequently SSTs [*Dallafior et al.*, 2015], affecting the inter-hemispheric SST gradient and thereby causing a shift of the Atlantic Inter-Tropical Convergence Zone (ITCZ) [e.g., *Chang et al.*, 2011; *Hwang et al.*, 2013]. Long-term anthropogenic aerosol forcing has furthermore been suggested to have strengthened the AMOC [*Delworth and Dixon*, 2006; *Cowan and Cai*, 2013; *Menary et al.*, 2013] and to have delayed ocean heat content increase and associated sea level rise in response to GHGs [e.g., *Delworth et al.*, 2005] during the twentieth century. The more recent reduction in North American and European anthropogenic aerosol emissions, on the other hand, can be linked to a slowdown of the AMOC by warming the Arctic and inducing sea ice melt [*Sévellec et al.*, 2017; *Acosta Navarro et al.*, 2016; *Wang et al.*, 2018].

In summary, a growing body of evidence indicates that aerosol-atmosphere-ocean interactions play a role in driving North Atlantic surface and subsurface multidecadal and longer-scale variability, but the detailed mechanisms are still poorly understood. Global aerosol emissions, in particular of the sulphate aerosol precursor sulphur dioxide (SO_2), were for most of the twentieth century dominated by sources in North America (NA) and Europe (EU) [*Lamarque et al.*, 2010; *Hoesly et al.*, 2017]. While emissions from both regions increased up to the 1970s and decreased rapidly thereafter in response to air pollution control policies, their relative impact and physical mechanisms thereof may not have been the same [*Shindell and Faluvegi*, 2009; *Westervelt et al.*, 2018; *Wang et al.*, 2015]. Addressing this question promises an improved mechanistic understanding of the Atlantic response to external -not only aerosol- forcing, with benefits for resolving conflicting findings and implications for regional climate projections and policy decisions.

We thus explore the sensitivity of Atlantic climate to historical changes in SO_2 emissions from NA and EU separately in a state-of-the-art coupled model, the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM1) with a comprehensive aerosol scheme [*Meehl et al.*, 2013; *Ekman*, 2014]. We use a set of purposefully-designed historical experiments whose ensemble size of 8, larger than typically employed in CMIP5, is expected to benefit the identification of the common forced signal given internal variability [e.g., *Knight*, 2009].

In the remainder of the manuscript, the model data and methods are briefly described (Section 2); the observed and simulated AMV are compared, the impacts of SO_2 emissions from NA and EU on simulated Atlantic SST variations identified, and relevant physical mechanisms analyzed (Section 3); and finally the results discussed and conclusions drawn (Section 4).

2. Data and Methods

2.1. Model Description and Experiment Set-up

We use the coupled NCAR/NSF-DoE Community Earth System Model (CESM1) version 1.2.2 [*Hurrell et al.*, 2013] with a horizontal atmospheric and oceanic resolution of 1.9°x2.5° and 0.6°x0.9°, respectively (more detail in Text S1). The atmospheric component is the Community Atmosphere Model version 5.3 (CAM5) [*Neale et al.*, 2012], which includes a 3-modal online tropospheric aerosol model (MAM3) with prognostic representations of both indirect aerosol effects [*Ghan et al.*, 2012; *Meehl et al.*, 2013].

Three sets of experiments covering the period 1850-1980 are used, each an ensemble of 8 members initialized from a 200-year pre-industrial (1850) control simulation (Fig. S1). The first experiment (ALL) is forced with time-varying historical estimates of GHG concentrations, volcanic aerosols, solar irradiance, land use, and anthropogenic and biomass burning aerosol emissions developed for CMIP5 [*Taylor et al.*, 2012] and should reproduce the observed climate best. The other experiments differ from ALL in that the SO_2 and SO_4 emissions from the anthropogenic sectors of energy, industry, domestic, transport, agriculture, and waste are kept at their pre-industrial level over either North America (noNA experiment) or over Europe (noEU experiment). The respective regions used are based on the Tier 1 regions from the Hemispheric Transport of Air Pollution 2 experiments [*Koffi et al.*, 2016], similar to *Bellouin et al.* [2016].

2.2. Observations

Two observational SST datasets are used: NOAA's Extended Reconstructed Sea Surface Temperature v4 [ERSST4; *Huang et al.*, 2015a] and the Met Office Hadley Centre's HadSST.3.1.1.0 [HadSST3; *Kennedy et al.*, 2011a]. HadSST3 consists of an ensemble of 100 realizations accounting for uncertainty due to possible pervasive low frequency biases, but not including other types of uncertainty [*Kennedy et al.*, 2011b]. ERSST4 is infilled to give full data coverage [*Huang et al.*, 2015b].

2.3. Methods

Area-mean, annual-mean time series are computed from monthly data, and smoothed by taking 5-year running means to suppress inter-annual variability. The spatial patterns of aerosol impact are analyzed using least-square linear trends during 1850-1975. Despite its simplicity, this approximation is adequate given the near-linear increase in SO_2 emissions from both NA and EU (Fig. S2) and correspondingly near-linear changes in global and regional sulphate loading, aerosol optical depth (AOD), radiative fluxes and temperature (not shown). The difference in the ensemble-mean response between ALL and noNA or ALL and noEU is interpreted as the impact of SO_2 emissions from NA or EU, respectively, and its significance measured by a two-tailed Students t-test at the 95% confidence level.

We calculate the AMV by regridding and masking the monthly model data to the observational (HadSST3) resolution and coverage, respectively; calculating monthly SST anomalies with respect to the 1854-1980 climatology; applying a 10-year low-pass (Lanczos) filter; removing the long-term linear trend; and averaging across the North Atlantic (0-65°N,0-80°W, area-weighted) as in *Bellomo et al.* [2017] and similar to e.g. *Knight et al.* [2005]. The AMOC index as a function of latitude is calculated from the model's MOC output -the net volumetric rate of water transported northwards- in the Atlantic-Arctic ocean at its maximum at any depth [*Medhaug and Furevik*, 2011; *Tandon and Kushner*, 2015].

3. Results

3.1. North Atlantic Sea Surface Temperatures

The ALL ensemble reproduces the observed AMV well, although it slightly underestimates the observed differences between the 1910/1920 and 1970 cool periods and the warmer period in between (Fig. 1a). Note that the AMV resembles strongly the area-mean SST anomalies due to the lack of a large trend during this period [Fig. S3; *Tandon and Kushner*, 2015], and shares variability with the rest of the global ocean (Figs. S4, S5). The simulated AMV correlates significantly with the observed AMV, with a correlation coefficient of c=0.52 (0.32-0.72 for the 90% ensemble range) in the ALL ensemble. The AMV has the same multi-decadal variations in all 24 simulations (visually from the ensemble envelopes in Fig. 1a), which indicates that it is dominated by external forcing in this model. If we further decompose the simulated AMV into the forced component approximated by the ensemble mean, and the internal variability component approximated by the residual after subtracting the ensemble mean, we find that the forced component is to a high degree correlated with the observations (c=0.69), the internal variability is not (c=0.02 (-0.31-0.34)). The forced component is thus detected in the observed AMV over internal variability.

The simulated response to all forcings except NA or EU emissions are also detected in the observations, with similar correlation coefficients (Fig. S6). While deciphering the external drivers of the AMV is thus not conclusively possible with our experiment set-up, the simulations do suggest a combination of factors. This includes a role for NA and EU SO_2 emissions -do note the similarity between the multi-decadal variability of Atlantic SSTs and of emissions around the long-term trend (Fig. S2)- amongst other, for instance volcanic (Fig. S7), forcings.

Comparison between ALL and the regional-aerosol ensembles shows that anthropogenic SO_2 emissions from NA and EU, while not significantly affecting the "phasing" of the simulated AMV, cause a steady long-term cooling of North Atlantic SSTs (Fig. 1b-e). The impact of NA emissions on basin-wide SSTs during 1850-1975 (≈ 0.25 K) is found to be larger than that of EU emissions (≈ 0.15 K) despite their similar historical emissions with around 40% global share each (Fig. S2) and their similar cooling of SSTs outside the Atlantic (< 0.1 K) (Figs. 1b-c, S3, S8). Note that this is similar for sub-surface ocean temperatures, with a decrease in simulated upper-ocean heat content in the Atlantic and elsewhere (Fig. S3).

In lower latitudes (0-40N°), the spatial patterns of the long-term Atlantic SST response to NA and EU SO2 emissions both show a cooling off the European and African west coast and across the subtropical North Atlantic and a cooling off the US-American East Coast (Fig. 1d-e). They also both show no cooling over the subpolar gyre (around 30°W,50°N) i.e. have a "cooling hole" which is symmetric to the observed "warming hole" [e.g., *Drijfhout et al.*, 2012], and no cooling (insignificant warming) in the tropical South Atlantic. Apart from these similarities, however, the patterns differ substantially: NA emissions cause strong cooling along the mid latitude storm track, spreading over most of the North Atlantic, while EU emissions cause a less widespread cooling concentrated along the African coast.

3.2. Atmospheric Aerosol Effects

A linear-trend analysis of aerosol content, cloud fraction, and radiative fluxes sheds light on the atmospheric component of the mechanism generating the SST changes discussed above. The increased NA and EU SO_2 emissions result in increased sulphate loading over the North Atlantic, manifest in increased (total) AOD, with the spatial patterns largely explained by climatological circulation (Fig. 2a-b): NA aerosols are advected over the Atlantic by mid-latitude storm tracks, while EU aerosols are transported into the sub-tropical Atlantic by trade winds. The decrease in clear-sky short-wave radiation over the same areas shows the direct effect (scattering) of sulphate aerosols (Fig. 2c-d). An increase in cloud droplet number concentration and cloud fraction over areas of large climatological cloud cover off the North American coast and in the North Atlantic strato-cumulus cloud deck (Figs. S9, S10) show aerosol-cloud interactions (ACIs), which contribute substantially to the change in all-sky short-wave radiation (Figs. 2e-f, S11).

This suggests that the simulated Atlantic SST response is larger for NA than for EU emissions because the prevailing winds transport NA aerosols more effectively over the Atlantic, and moreover to regions with more climatological cloud cover. Note also that significant changes in sea salt and dust aerosols over the North and tropical South Atlantic (Fig. S12) suggest the possibility of still largely unexplored feedbacks between anthropogenic aerosols, climate, and natural aerosols [*Wang et al.*, 2012; *Martin et al.*, 2014; *Allen et al.*, 2015; *Yuan et al.*, 2016]; the increased dust burden over the equatorial north Atlantic, for instance, might induce an ITCZ shift opposite to that found in response to NA and EU emissions [*Pan et al.*, 2018].

3.3. AMOC

Potential interactions between simulated North Atlantic SSTs, large-scale ocean circulation, and sulphate aerosols -as for example suggested by the simulated aerosol-induced cooling east of the Grand Banks (Figs. 1c-d, S3), thought of as a key region for the North Atlantic ocean circulation [*Buckley and Marshall*, 2016]- are investigated by means of the AMOC. The simulated AMOC shows pronounced multi-decadal variability, with a strengthening until about 1920, a weakening until around 1950, and again a strengthening thereafter (Fig. 3a). As for the AMV (Section 3.1), this phasing is the same in all 24 simulations, indicating that a large fraction of the AMOC is externally forced in the model rather than due to internal variability.

Earlier research suggests this external forcing to be mediated by the AMV, with cool and warm Atlantic SSTs causing an AMOC strengthening and weakening, respectively [e.g., *Zhang and Wang*, 2013; *Tandon and Kushner*, 2015]. This is because cooler SSTs over the high-latitude North Atlantic imply an increased ocean density in the upper layers which reduces stability in the water column, encourages convection, and strengthens the thermohaline circulation [e.g., *Delworth and Dixon*, 2006]. Comparison with the AMV index (Fig. 1) suggests indeed a lagged anti-correlation between the either simulated or observed AMV and the simulated AMOC. This is confirmed by a lead-lag analysis (Fig. S13), which shows the ensemble-mean, i.e. forced, component of AMV and AMOC in all historical experiments to be anti-correlated with an AMV lead by 10 years (or an AMOC lead by 30 years, which we discard for physical reasons). In the unforced case, the AMOC drives the AMV near zero lag, and both mechanisms are superposed in the historical simulations. The AMV seems thus also here to mediate the external forcing of the AMOC. While the NAO [*Hurrell*, 1995] might play a role in linking the AMV with the AMOC at decadal or longer time scales [*Mignot and Frankignoul*, 2005; *Delworth* *and Zeng*, 2016; *Iles and Hegerl*, 2017], our simulations do not show a long-term change or significant response to the sulphate aerosol forcing in the NAO (Fig. S14), which is unsurprising given that the connection is known to be commonly underestimated in current models [*Eade et al.*, 2014].

As with the AMV, attributing the external forcing of the multi-decadal AMOC variability to a specific forcing agent is not conclusively possible with our experiment design. SO_2 emissions from NA and EU together, however, are suggested to be the dominant driver of the AMOC strengthening before 1920 (purple line in Fig. 3a). Regarding longer-term changes, SO_2 emissions from NA and EU separately have a discernible impact: From 1900 onwards, the AMOC index is persistently higher by about 2.5% when either NA or EU SO_2 emissions are included (Fig. 3a), at all depths and latitudes up to about 55°N (Fig. 3b). The associated increase in northward ocean heat transport will compensate for some of the radiative cooling over the Atlantic (Fig. 2). This means that magnitude and pattern of the long-term SST responses to SO_2 emissions from NA and EU described above (Fig. 1b-e) are a combination of atmospheric forcing and ocean feedback.

3.4. Large-Scale Atmospheric Adjustment and Impact on Global Precipitation

The simulations show a temperature response to NA and EU emissions not only over the Atlantic, but far downstream of the respective emission regions across most of the northern hemisphere (NH) (Figs. 1b, S8). The inter-hemispheric temperature contrast is thereby steadily decreased throughout the twentieth century (Fig. 4a). This is also relevant for the Atlantic region in that it causes an enhancement of the southern flank of the ITCZ and thus its de facto southward shift [e.g., *Allen et al.*, 2015b; *Westervelt* *et al.*, 2017; *Undorf et al.*, 2018a, b]. Note that this response again includes a partial compensation from the AMOC feedback [Fig. 3; *Dong and Sutton*, 2005; *Marshall et al.*, 2014].

The ITCZ shift is visible in equator-symmetric changes in cloud fraction, water vapour, precipitation, and radiative fluxes (Figs. 2e-h, S9, S10, S11). The resulting negative and positive fluxes north and south of the equator, respectively, (Fig. 2i-j) can be considered a positive feedback to the Atlantic and NH cooling [e.g., *Clark et al.*, 2018]. The simulated global precipitation response is dominated by this ITCZ shift, showing a prominent change of tropical rainfall pattern in all ocean basins which is remarkably similar for NA and EU emissions (Figs. 4b-c, S11).

4. Summary, Discussion and Conclusions

The Atlantic climate responses to historical (1850-1975) sulphate aerosols from North America (NA) and Europe (EU) have been contrasted in a coupled climate model by comparing transient 8-member ensemble simulations with either all forcings evolving historically or anthropogenic SO_2 emissions from NA and EU separately kept at pre-industrial levels. The study was motivated by existing literature suggesting a role for anthropogenic aerosols in past multi-decadal variability of Atlantic SSTs which affects climate worldwide, and a knowledge gap concerning the relative roles of NA and EU emissions despite its relevance for policy applications.

In summary, we find that sulphate aerosols from either source cause a long-term cooling of North Atlantic SSTs, with the patterns a combination of atmospheric aerosol effects and an aerosol-induced strengthening of the AMOC. The response is larger for NA than for EU emissions, with stronger indirect aerosol effects due to a wider aerosol spread over the Atlantic and collocation with climatological cloud cover. A southward shift of the ITCZ, affecting tropical precipitation globally, and causing a small positive feedback to the North Atlantic cooling, is also found. The (multi)decadal variability components of Atlantic SSTs, i.e. the AMV, and of the AMOC are both found to be primarily externally forced, possibly by a combination of forcings factors including NA and EU sulphate aerosols. The forced component of the AMV is detected in observations over internal variability.

The external forcing of the model's AMV and the lead-lag relationships between its AMV and AMOC shows that earlier findings [*Murphy et al.*, 2017; *Bellomo et al.*, 2017; *Tandon and Kushner*, 2015] hold also for simulations initialized from different ocean states. The consequential small role allowed for *internal* ocean variability in explaining AMOC variations given external forcings -historical and prospective- has received little attention in the literature so far. In showing that NA and EU emissions impact the simulated historical AMOC to similar amounts, we furthermore extend the results of *Cowan and Cai* [2013]. The simulated "cooling hole" (Section 3.1) in response to NA and EU SO_2 emissions suggests furthermore the observed "warming hole" [e.g., *Drijfhout et al.*, 2012] not to be aerosol driven, but due to the AMOC feedback, which seems to mute aerosol cooling as it mutes GHG warming.

Our findings rely on the model's representation of many complex and highly uncertain processes that may vary between models. We cannot test the historical forcing of the AMOC due to the lack of observations [*Srokosz et al.*, 2012; *Munoz et al.*, 2011], but the simulated (1920-1980) AMOC variations are consistent with the CMIP5 MMM [*Tandon and Kushner*, 2015], and the simulations capture for example historical observations of sub-polar sea surface salinity [Fig. S15; *Friedman et al.*, 2017] in addition to Atlantic and global SSTs.

Inter-model differences in the atmospheric response arise from pre-industrial aerosol loading, historical SO_2 spread, and especially the parametrisation of ACIs [e.g., *Wilcox et al.*, 2015]. The model's aerosol net total effective radiative forcing and its climate sensitivity are amongst the largest across a range of CMIP5 models, but not exceptional [*Zelinka et al.*, 2014; *Meehl et al.*, 2013; *Forster et al.*, 2013]. On the other hand, CESM1 seems to underestimate the observed SST variability over the Atlantic (Fig. 1a), which could either imply internal variability not captured by the model, or, given the temporal covaration of the forced (ensemble-mean) signal and the observations, an underestimation of the forced response. Since some of the forced response is from (both anthropogenic and volcanic) aerosols [Section 3.1; *Booth et al.*, 2012], this could further suggest that the model underestimates the response to aerosols. Lower or higher aerosol forcing may result in decreased and increased, respectively, absolute values of SST cooling compared to those found here.

Modelling uncertainties in the ratio between ARIs and ACIs might furthermore affect the attribution of Atlantic SST cooling to NA vs. EU emissions. Compared to other CMIP5 models, CESM1 has large aerosol indirect forcing concurrent with low direct aerosol forcing [*Zelinka et al.*, 2014]; note, however, that NA emissions cause larger radiative flux changes even in clear-sky short-wave radiation which is primarily a result of the direct aerosol effect (Fig. 2c-d). The larger response of the ITCZ to NA than to EU emissions found here (Fig. S11) was also found in two other models in addition to CESM1 by *Westervelt et al.* [2018] for the precipitation response to a removal of present-day SO_2 emissions in time-slice experiments. Judging from their projected 21st century shifts [*Allen*, 2015], other CMIP5 models which also represent both aerosol indirect effects are expected to simulate even larger historical changes in the ITCZ.

To conclude, this study sheds light on the contribution of regional aerosol emissions from NA and EU to the changes in North Atlantic SSTs during the industrial period, providing insights of the associated physical mechanisms including the large-scale atmosphere and ocean circulation. The findings are not only relevant for projections of future change related to a continued decline of SO_2 emissions [*Vuuren et al.*, 2011; *Westervelt et al.*, 2017], but also for the mechanistic understanding of the role of forcing in Atlantic variability and as such for future projections related to other forcing agents.

Acknowledgments. We thank Andrew Friedman for discussion and helpful comments. The CESM project is supported by the National Science Foundation and the Office of Science (BER) of the U.S. Department of Energy. We acknowledge use of the ARCHER UK National Supercomputing Service. S. Undorf and G. C. Hegerl were supported by the European Research Council (ERC) funded project (EC-320691) TITAN. G. C. Hegerl was furthermore funded by the Wolfson Foundation and the Royal Society as Royal Society Wolfson Research Merit Award holder (WM130060). M. A. Bollasina was supported by the UK-China Research and Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund. The observa-

tional data sets used in this study are publicly available and properly cited and referred to in the reference list. The model data for SSTs, AOD, precipitation, and the MOC are available at `https://doi.org/10.6084/m9.figshare.7117673`; other fields from the experiments are available upon request from the second author (massimo.bollasina@ed.ac.uk).

References

Acosta Navarro, J. C., V. Varma, I. Riipinen, Ø. Seland, A. Kirkevåg, H. Struthers, T. Iversen, H.-C. Hansson, and A. M. L. Ekman (2016), Amplification of Arctic warming by past air pollution reductions in Europe, *Nat. Geosci.*, *9*, 277–281, doi: 10.1038/NGEO2673.

Allen, R. J. (2015), A 21st century northward tropical precipitation shift caused by future anthropogenic aerosol reductions, *Journal of Geophysical Research: Atmospheres*, *120*(18), 9087–9102, doi:10.1002/2015JD023623.

Allen, R. J., A. T. Evan, and B. B. B. Booth (2015b), Interhemispheric aerosol radiative forcing and tropical precipitation shifts during the late Twentieth Century, *J. Clim.*, *28*(20), 8219–8246, doi:10.1175/JCLI-D-15-0148.1.

Allen, R. J., W. Landuyt, and S. T. Rumbold (2015), An increase in aerosol burden and radiative effects in a warmer world, *Nature Climate Change*, (November), 1–6, doi:10.1038/nclimate2827.

Ba, J., N. S. Keenlyside, M. Latif, W. Park, H. Ding, K. Lohmann, J. Mignot, M. Menary, O. H. Otterå, B. Wouters, D. Salas y Melia, A. Oka, A. Bellucci, and E. Volodin (2014), A multi-model comparison of Atlantic multidecadal variability, *Climate Dynamics*, *43*(9-10), 2333–2348, doi:10.1007/s00382-014-2056-1.

Bellomo, K., L. N. Murphy, M. A. Cane, A. C. Clement, and L. M. Polvani (2017), Historical forcings as main drivers of the Atlantic multidecadal variability in the CESM large ensemble, *Clim Dyn*, doi:10.1007/s00382-017-3834-3.

Bellouin, N., L. Baker, Ø. Hodnebrog, D. Olivié, R. Cherian, C. Macintosh, B. Samset, A. Esteve, B. Aamaas, J. Quaas, and G. Myhre (2016), Regional and seasonal radiative forcing by perturbations to aerosol and ozone precursor emissions, *Atmos Chem Phys*, *16*, 13,885–13,910, doi:10.5194/acp-16-13885-2016.

Bjerknes, J. (1964), Atlantic Air-Sea Interaction, *Advances in Geophysics*, *10*(C), 1–82, doi:10.1016/S0065-2687(08)60005-9.

Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin (2012), Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability, *Nature*, *484*(7393), 228–232, doi:10.1038/nature10946.

Buckley, M. W., and J. Marshall (2016), Observations, inferences, andmechanisms of the AtlanticMeridionalOverturning Circulation: A review, *Reviews of Geophysics*, *54*, 5–63, doi:10.1002/2015RG000493.

Chang, C.-Y., J. C. H. Chiang, M. F. Wehner, A. R. Friedman, and R. Ruedy (2011), Sulfate aerosol control of tropical Atlantic climate over the twentieth century, *Journal of Climate*, *24*(10), 2540–2555, doi:10.1175/2010JCLI4065.1.

Christensen, J., K. K. Kumar, E. Aldrian, S.-I. An, I. Cavalcanti, M. de Castro, P. G. W. Dong, A. Hall, J. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D. Stephenson, S.-P. Xie, and T. Zhou (2013), Climate Phenomena and their Relevance for Future Regional Climate Change, in *Climate Change 2013: The Physical Science Basis. Con-*

tribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, chap. 14, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark, S. K., Y. Ming, I. M. Held, and P. J. Phillipps (2018), The role of the water vapor feedback in the ITCZ response to hemispherically asymmetric forcings, *Journal of Climate*, *31*(9), 3659–3678, doi:10.1175/JCLI-D-17-0723.1.

Clement, A., K. Bellomo, L. N. Murphy, M. A. Cane, T. Mauritsen, G. Radel, and B. Stevens (2015), The Atlantic Multidecadal Oscillation without a role for ocean circulation, *Science*, *350*(6258), 320–324, doi:10.1126/science.aab3980.

Clement, A., K. Bellomo, L. N. Murphy, M. A. Cane, T. Mauritsen, G. Radel, and B. Stevens (2016), Response to Comment: The Atlantic Multidecadal Oscillation without a role for ocean circulation, *Science*, *350*(6258), 320–324, doi:10.1126/science.aab3980.

Cowan, T., and W. Cai (2013), The response of the large-scale ocean circulation to 20th century Asian and non-Asian aerosols, *Geophysical Research Letters*, *40*(11), 2761–2767, doi:10.1002/grl.50587.

Dallafior, T. N., D. Folini, R. Knutti, and M. Wild (2015), Dimming over the oceans: Transient anthropogenic aerosol plumes in the twentieth century, *Journal of Geophysical Research Atmospheres*, *120*(8), 3465–3484, doi:10.1002/2014JD022658.

Delworth, T., S. Manabe, and R. J. Stouffer (1993), Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, *Journal of Climate*, *6*(11), 1993–2011, doi:10.1175/1520-0442(1993)006⟨1993:IVOTTC⟩2.0.CO;2.

Delworth, T. L., and K. W. Dixon (2006), Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation?, *Geophysical Research Letters*, *33*(2), 3–6, doi:10.1029/2005GL024980.

Delworth, T. L., and F. Zeng (2016), The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic meridional overturning circulation, *Journal of Climate*, *29*(3), 941–962, doi:10.1175/JCLI-D-15-0396.1.

Delworth, T. L., V. Ramaswamy, and G. L. Stenchikov (2005), The impact of aerosols on simulated ocean temperature and heat content in the 20th century, *Geophysical Research Letters*, *32*(24), 1–4, doi:10.1029/2005GL024457.

Delworth, T. L., F. Zeng, L. Zhang, R. Zhang, G. A. Vecchi, and X. Yang (2017), The Central Role of Ocean Dynamics in Connecting the North Atlantic Oscillation to the Extratropical Component of the Atlantic Multidecadal Oscillation, *J Climate*, *30*, 3789–3805, doi:10.1175/JCLI-D-16-0358.1.

Ding, Y., J. A. Carton, G. A. Chepurin, G. Stenchikov, A. Robock, L. T. Sentman, and J. P. Krasting (2014), Ocean response to volcanic eruptions in Coupled Model Intercomparison Project 5 simulations, *Journal of Geophysical Research*, *119*, 5622–5637, doi:10.1002/2013JC009780.Received.

Dong, B., and R. T. Sutton (2005), Mechanism of interdecadal thermohaline circulation variability in a coupled ocean-atmosphere GCM, *Journal of Climate*, *18*(8), 1117–1135, doi:10.1175/JCLI3328.1.

Drijfhout, S., G. J. van Oldenborgh, and A. Cimatoribus (2012), Is a Decline of AMOC Causing the Warming Hole above the North Atlantic in Observed and Modeled Warming Patterns?, *Journal of Climate*, *25*(24), 8373–8379, doi:10.1175/JCLI-D-12-00490.1.

Dunstone, N. J., D. M. Smith, B. B. B. Booth, L. Hermanson, and R. Eade (2013), Anthropogenic aerosol forcing of Atlantic tropical storms, *Nature Geoscience*, *6*, 534–539, doi:10.1038/ngeo1854.

Eade, R., D. Smith, A. Scaife, E. Wallace, N. Dunstone, L. Hermanson, and N. Robinson (2014), Do seasonal-to-decadal climate predictions underestimate the predictability of the real world?, *Geophys Res Lett*, *41*, 5620–5628, doi:10.1002/2014GL061146.

Ekman, A. M. L. (2014), Do sophisticated parameterizations of aerosolcloud interactions in CMIP5 models improve the representation of recent observed temperature trends?, *Journal of Geophysical Research: Atmospheres*, *119*, 817–832, doi:10.1002/2013JD020511.Received.

Forster, P. M., T. Andrews, P. Good, J. M. Gregory, L. S. Jackson, and M. Zelinka (2013), Evaluating adjusted forcing and model spread for historical and future scenarios in the CMIP5 generation of climate models, *Journal of Geophysical Research Atmospheres*, *118*(3), 1139–1150, doi:10.1002/jgrd.50174.

Friedman, A. R., G. Reverdin, M. Khodri, and G. Gastineau (2017), A new record of Atlantic sea surface salinity from 1896 to 2013 reveals the signatures of climate variability and long-term trends, *Geophysical Research Letters*, *44*(4), 1866–1876, doi:10.1002/2017GL072582.

Ghan, S. J., X. Liu, R. C. Easter, R. Zaveri, P. J. Rasch, J. H. Yoon, and B. Eaton (2012), Toward a minimal representation of aerosols in climate models: Comparative decomposition of aerosol direct, semidirect, and indirect radiative forcing, *Journal of Climate*, *25*(19), 6461–6476, doi:10.1175/JCLI-D-11-00650.1.

Gulev, S. K., M. Latif, N. Keenlyside, W. Park, and K. P. Koltermann (2013), North Atlantic Ocean control on surface heat flux on multidecadal timescales., *Nature*, *499*(7459), 464–7, doi:10.1038/nature12268.

Hoesly, R. M., S. J. Smith, L. Feng, Z. Klimont, G. Janssens-Maenhout, T. Pitkanen, J. J. Seibert, L. Vu, R. J. Andres, R. M. Bolt, T. C. Bond, L. Dawidowski, N. Kholod, J.-i. Kurokawa, M. Li, L. Liu, Z. Lu, M. C. P. Moura, P. R. O'Rourke, and Q. Zhang (2017), Historical (1750 2014) anthropogenic emissions of reactive gases and aerosols from the Community Emission Data System (CEDS), *Geosci. Model Dev. Discuss.*, (March), 1–41, doi:10.5194/gmd-2017-43.

Huang, B., V. F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T. C. Peterson, T. M. Smith, P. W. Thorne, S. D. Woodruff, and H.-M. Zhang (2015a), Extended Reconstructed Sea Surface Temperature (ERSST), Version 4., *NOAA National Centers for Environmental Information*, doi:10.7289/V5KD1VVF.

Huang, B., V. F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T. C. Peterson, T. M. Smith, P. W. Thorne, S. D. Woodruff, and H. M. Zhang (2015b), Extended reconstructed sea surface temperature version 4 (ERSST.v4). Part I: Upgrades and intercomparisons, *Journal of Climate*, *28*(3), 911–930, doi:10.1175/JCLI-D-14-00006.1.

Hurrell, J. W. (1995), Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation., *Science (New York, N.Y.)*, *269*(5224), 676–9, doi:10.1126/science.269.5224.676.

Hurrell, J. W., M. M. Holland, P. R. Gent, S. Ghan, J. E. Kay, P. J. Kushner, J.-F. Lamarque, W. G. Large, D. Lawrence, K. Lindsay, W. H. Lipscomb, M. C. Long, N. Mahowald, D. R. Marsh, R. B. Neale, P. Rasch, S. Vavrus, M. Vertenstein, D. Bader, W. D. Collins, J. J. Hack, J. Kiehl, and S. Marshall (2013), The Community Earth System Model, *Bull. Am. Meteorol. Soc.*, *94*(9), 1339–1360, doi:10.1175/BAMS-D-12-00121.1.

Hwang, Y.-T., D. M. W. Frierson, and S. M. Kang (2013), Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century, *Geophysical Research Letters*, *40*(11), 2845–2850, doi:10.1002/grl.50502.

Iles, C., and G. Hegerl (2017), Role of the North Atlantic Oscillation in decadal temperature trends Role of the North Atlantic Oscillation in decadal temperature trends, *Environ. Res. Lett.*, *12*(114010).

Kavvada, A., A. Ruiz-Barradas, and S. Nigam (2013), AMO's structure and climate footprint in observations and IPCC AR5 climate simulations, *Climate Dynamics*, *41*(5-6), 1345–1364, doi:10.1007/s00382-013-1712-1.

Kennedy, J. J., N. A. Rayner, R. O. Smith, D. E. Parker, and M. Saunby (2011a), Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 1. Measurement and sampling uncertainties, *J. Geophys. Res.*, *116*(D14103), 1–13, doi:10.1029/2010JD015218.

Kennedy, J. J., N. A. Rayner, R. O. Smith, D. E. Parker, and M. Saunby (2011b), Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2 . Biases and homogenization, *J. Geophys. Res.*, *116*(D14104), 1–22, doi:10.1029/2010JD015220.

Knight, J. R. (2009), The Atlantic multidecadal oscillation inferred from the forced climate response in coupled general circulation models, *Journal of Climate*, *22*(7), 1610–1625, doi:10.1175/2008JCLI2628.1.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophysical Research Letters*, *32*(20), 1–4, doi:10.1029/2005GL024233.

Knight, J. R., C. K. Folland, and A. A. Scaife (2006), Climate impacts of the Atlantic multidecadal oscillation, *Geophysical Research Letters*, *33*(17), 2–5, doi:10.1029/2006GL026242.

Knudsen, M. F., B. H. Jacobsen, M.-S. Seidenkrantz, and J. Olsen (2014), Evidence for external forcing of the Atlantic Multidecadal Oscillation since termination of the Little Ice Age., *Nature communications*, *5*, 3323, doi:10.1038/ncomms4323.

Koffi, B., F. Dentener, G. Janssens-Maenhout, D. Guizzardi, M. Crippa, T. Diehl, S. Galmarini, and E. Solazzo (2016), Hemispheric Transport Air Pollution (HTAP): Specification of the HTAP2 experiments Ensuring harmonized modelling, *Tech. rep.*, Joint Research Centre (JRC), Luxembourg, doi:10.2788/725244.

Lamarque, J.-F., T. C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M. G. Schultz, D. Shindell, S. J. Smith, E. Stehfest, J. Van

Aardenne, O. R. Cooper, M. Kainuma, N. Mahowald, J. R. McConnell, V. Naik, K. Riahi, and D. P. van Vuuren (2010), Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, *Atmos Chem Phys*, *10*(15), 7017–7039, doi:10.5194/acp-10-7017-2010.

Marini, C., and C. Frankignoul (2014), An attempt to deconstruct the Atlantic Multidecadal Oscillation, *Climate Dynamics*, *43*(3-4), 607–625, doi:10.1007/s00382-013-1852-3.

Marshall, J., A. Donohoe, D. Ferreira, and D. McGee (2014), The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone, *Climate Dynamics*, *42*(7-8), 1967–1979, doi:10.1007/s00382-013-1767-z.

Martin, E. R., C. Thorncroft, and B. B. B. Booth (2014), The Multidecadal Atlantic SSTSahel Rainfall Teleconnection in CMIP5 Simulations, *Journal of Climate*, *27*(2), 784–806, doi:10.1175/JCLI-D-13-00242.1.

Medhaug, I., and T. Furevik (2011), North Atlantic 20th century multidecadal variability in coupled climate models: Sea surface temperature and ocean overturning circulation, *Ocean Science*, *7*(3), 389–404, doi:10.5194/os-7-389-2011.

Meehl, G. A., W. M. Washington, J. M. Arblaster, A. Hu, H. Teng, J. E. Kay, A. Gettelman, D. M. Lawrence, B. M. Sanderson, and W. G. Strand (2013), Climate Change Projections in CESM1(CAM5) Compared to CCSM4, *J Climate*, *26*, 6287–6308, doi:10.1175/JCLI-D-12-00572.1.

Menary, M. B., C. D. Roberts, M. D. Palmer, P. R. Halloran, L. Jackson, R. a. Wood, W. a. Müller, D. Matei, and S.-K. Lee (2013), Mechanisms of aerosol-forced AMOC variability in a state of the art climate model, *Journal of Geophysical Research: Oceans*, *118*(4), 2087–2096, doi:10.1002/jgrc.20178.

Mignot, J., and C. Frankignoul (2005), The Variability of the Atlantic Meridional Overturning Circulation, the North Atlantic Oscillation, and the El Niño Southern Oscillation in the Bergen Climate Model, *Journal of Climate*, *18*, 2361–2375, doi:10.1175/JCLI3405.1.

Munoz, E., B. Kirtman, and W. Weijer (2011), Varied representation of the Atlantic Meridional Overturning across multidecadal ocean reanalyses, *Deep-Sea Research Part II: Topical Studies in Oceanography*, *58*(17-18), 1848–1857, doi:10.1016/j.dsr2.2010.10.064.

Murphy, L. N., K. Bellomo, M. Cane, and A. Clement (2017), The role of historical forcings in simulating the observed Atlantic multidecadal oscillation, *Geophys Res Lett*, *44*, 2472–2480, doi:10.1002/2016GL071337.

Neale, R. B., A. Gettelman, S. Park, C.-c. Chen, P. H. Lauritzen, D. L. Williamson, A. J. Conley, D. Kinnison, D. Marsh, A. K. Smith, F. Vitt, R. Garcia, J.-f. Lamarque, M. Mills, S. Tilmes, H. Morrison, P. Cameron-smith, W. D. Collins, M. J. Iacono, R. C. Easter, X. Liu, S. J. Ghan, P. J. Rasch, and M. a. Taylor (2012), Description of the NCAR Community Atmosphere Model (CAM 5.0), *NCAR Technical Note*, *NCAR/TN-48*, 274, doi:10.5065/D6N877R0.

Nigam, S., B. Guan, and A. Ruiz-Barradas (2011), Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains, *Geophysical Research Letters*, *38*(16), 1–6, doi:10.1029/2011GL048650.

Otterå, O. H., M. Bentsen, H. Drange, and L. Suo (2010), External forcing as a metronome for Atlantic multidecadal variability, *Nature Geoscience*, *3*(10), 688–694, doi:10.1038/ngeo955.

Pan, B., Y. Wang, J. Hu, Y. Lin, J.-S. Hsieh, T. Logan, X. Feng, J. H. Jiang, Y. L. Yung, and R. Zhang (2018), Impacts of Saharan dust on Atlantic regional climate and implications for tropical cyclones, *J. Clim.*, *31*(18), 7621–7644, doi:10.1175/JCLI-D-16-0776.1.

Rahmstorf, S., J. E. Box, G. Feulner, M. E. Mann, A. Robinson, S. Rutherford, and E. J. Schaffernicht (2015), Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation, *Nature Climate Change*, *5*(5), 475–480, doi:10.1038/nclimate2554.

Sévellec, F., A. V. Fedorov, and W. Liu (2017), Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation, *Nat. Clim. Chang.*, *7*(8), 604–610, doi:10.1038/NCLIMATE3353.

Shindell, D., and G. Faluvegi (2009), Climate response to regional radiative forcing during the twentieth century, *Nature Geoscience*, *2*(4), 294–300, doi:10.1038/ngeo473.

Smith, D. M., R. Eade, N. J. Dunstone, D. Fereday, J. M. Murphy, H. Pohlmann, and A. A. Scaife (2010), Skilful multi-year predictions of Atlantic hurricane a frequency, *Nature Geoscience*, *3*(12), 846–849, doi:10.1038/ngeo1004.

Srokosz, M., M. Baringer, H. Bryden, S. Cunningham, T. Delworth, S. Lozier, J. Marotzke, and R. Sutton (2012), Past, Present, and Future Changes in the Atlantic Meridional Overturning Circulation, *Bull. Am. Meteorol. Soc.*, *93*(11), 1663–1676, doi:10.1175/BAMS-D-11-00151.1.

Steinman, B. A., M. E. Mann, and S. K. Miller (2015), Hemisphere temperatures, *Science*, *347*(February), 988–991, doi:10.5061/dryad.6f576.SUPPLEMENTARY.

Stenchikov, G., T. L. Delworth, V. Ramaswamy, R. J. Stouffer, A. Wittenberg, and F. Zeng (2009), Volcanic signals in oceans, *Journal of Geophysical Research Atmospheres*, *114*(16), 1–13, doi:10.1029/2008JD011673.

Sutton, R. T., and D. L. Hodson (2007), Climate response to basin-scale warming and cooling of the North Atlantic Ocean, *J Climate*, *20*(5), 891–907, doi:10.1175/JCLI4038.1.

Swingedouw, D. (2015), Oceanography: Fresh news from the Atlantic, *Nature Climate Change*, *5*(5), 411–412, doi:10.1038/nclimate2626.

Tandon, N. F., and P. J. Kushner (2015), Does external forcing interfere with the AMOC's influence on North Atlantic sea surface temperature?, *Journal of Climate*, *28*(16), 6309–6323, doi:10.1175/JCLI-D-14-00664.1.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An Overview of CMIP5 and the Experiment Design, *Bulletin of the American Meteorological Society*, *93*(4), 485–498, doi:10.1175/BAMS-D-11-00094.1.

Ting, M., Y. Kushnir, R. Seager, and C. Li (2009), Forced and Internal Twentieth-Century SST Trends in the North Atlantic, *Journal of Climate*, *22*(6), 1469–1481, doi:10.1175/2008JCLI2561.1.

Ting, M., Y. Kushnir, R. Seager, and C. Li (2011), Robust features of Atlantic multidecadal variability and its climate impacts, *Geophysical Research Letters*, *38*(17), doi:10.1029/2011GL048712.

Ting, M., Y. Kushnir, and C. Li (2014), North Atlantic Multidecadal SST Oscillation: External forcing versus internal variability, *Journal of Marine Systems*, *133*, 27–38, doi:10.1016/j.jmarsys.2013.07.006.

Undorf, S., D. Polson, M. Bollasina, Y. Ming, A. Schurer, and G. C. Hegerl (2018a), Detectable impact of local and remote anthropogenic aerosols on the 20th century changes of West African and South Asian monsoon precipitation, *Journal of Geophysical Research: Atmospheres*, *123*, 1–19, doi:10.1029/2017JD027711.

Undorf, S., M. A. Bollasina, and G. C. Hegerl (2018b), Impacts of the 1900-1974 increase in anthropogenic aerosol emissions from North America and Europe on northern hemisphere summer climate, *Journal of Climate*, doi:10.1175/JCLI-D-17-0850.1.

Vuuren, D. P. V., J. Edmonds, M. Kainuma, K. Riahi, N. Nakicenovic, S. J. Smith, and S. K. Rose (2011), The representative concentration pathways: an overview, *Clim. Change*, *109*, 5–31, doi:10.1007/s10584-011-0148-z.

Wang, C., S. Dong, A. T. Evan, G. R. Foltz, and S. K. Lee (2012), Multidecadal covariability of north atlantic sea surface temperature, African dust, Sahel Rainfall, and Atlantic hurricanes, *Journal of Climate*, *25*(15), 5404–5415, doi:10.1175/JCLI-D-11-00413.1.

Wang, J., B. Yang, F. C. Ljungqvist, J. Luterbacher, T. J. Osborn, K. R. Briffa, and E. Zorita (2017), Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years, *Nature Geoscience*, *10*(7), 512–517, doi:10.1038/ngeo2962.

Wang, Y., J. H. Jiang, and H. Su (2015), Atmospheric responses to the redistribution of anthropogenic aerosols, *J. Geophys. Res.*, *120*(18), 9625–9641, doi:10.1002/2015JD023665.

Wang, Y., J. H. Jiang, H. Su, Y.-S. Choi, L. Huang, J. Guo, and Y. L. Yung (2018), Elucidating the role of anthropogenic aerosols in Arctic sea ice variations, *J. Clim.*, *31*(1), 99–114, doi:10.1175/JCLI-D-17-0287.1.

Westervelt, D. M., A. J. Conley, A. M. Fiore, J. F. Lamarque, D. Shindell, M. Previdi, G. Faluvegi, G. Correa, and L. W. Horowitz (2017), Multimodel precipitation responses to removal of U.S. sulfur dioxide emissions, *Journal of Geophysical Research*, *122*(9), 5024–5038, doi:10.1002/2017JD026756.

Westervelt, D. M., A. J. Conley, A. M. Fiore, J.-F. Lamarque, D. T. Shindell, M. Previdi, N. R. Mascioli, G. Faluvegi, G. Correa, and L. W. Horowitz (2018), Connecting regional aerosol emissions reductions to local and remote precipitation responses, *Atmospheric Chemistry and Physics Discussions*, (June), 1–25, doi:10.5194/acp-2018-516.

Wilcox, L. J., E. J. Highwood, B. B. B. Booth, and K. S. Carslaw (2015), Quantifying sources of inter-model diversity in the cloud albedo effect, *Geophys. Res. Lett.*, *42*, 1568–1575, doi:10.1002/2015GL063301.

Yuan, T., L. Oreopoulos, M. Zelinka, H. Yu, J. R. Norris, M. Chin, S. Platnick, and K. Meyer (2016), Positive low cloud and dust feedbacks amplify tropical North Atlantic Multidecadal Oscillation, *Geophysical Research Letters*, *43*(3), 1349–1356, doi:10.1002/2016GL067679.

Zelinka, M. D., T. Andrews, P. M. Forster, and K. E. Taylor (2014), Quantifying components of aerosol-cloud-radiation interactions in climate models, *J Geophys Res Atmos*, *119*(12), 7599–7615, doi:10.1002/2014JD021710.

Zhang, C., T. L. Delworth, R. Sutton, D. L. R Hodson, K. W. Dixon, I. M. Held, Y. Kushnir, R. Zhang, J. Marshall, Y. Ming, R. Msadek, J. Robson, A. J. Rosati, M. Ting, and G. A. Vecchi (2013), Have Aerosols Caused the Observed Atlantic Multidecadal Variability?, *J. Atmospheric Sci.*, *70*(4), 1135–1144, doi:10.1175/JAS-D-12-0331.1.

Zhang, L., and C. Wang (2013), Multidecadal North Atlantic sea surface temperature and Atlantic meridional overturning circulation variability in CMIP5 historical simulations, *Journal of Geophysical Research: Oceans*, *118*(10), 5772–5791, doi:10.1002/jgrc.20390.

Zhang, R. (2017), On the persistence and coherence of subpolar sea surface temperature and salinity anomalies associated with the Atlantic multidecadal variability, *Geophysical Research Letters*, *44*(15), 7865–7875, doi:10.1002/2017GL074342.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophysical Research Letters*, *33*(17), 1–5, doi:10.1029/2006GL026267.

Zhang, R., R. Sutton, G. Danabasoglu, T. L. Delworth, W. M. Kim, J. Robson, and S. G. Yeager (2016), Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation", *Science*, *352*(6293), doi:10.1126/science.aab3980.

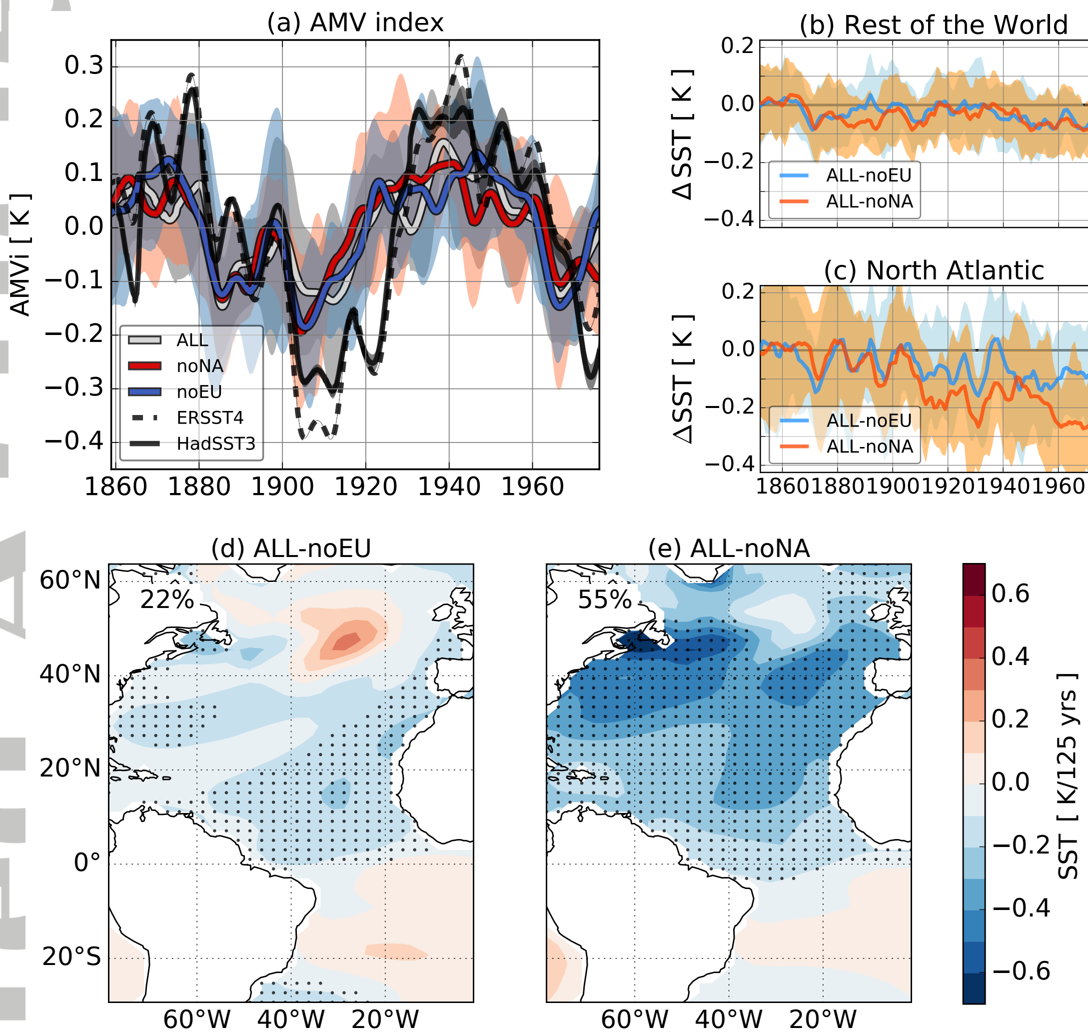

Figure 1. Atlantic sea surface temperatures (SSTs): (a) Observed and simulated Atlantic Multi-decadal Variability (AMV) and (b-e) simulated SST change due to regional SO_2 emissions. (a) AMV from observations ERSST4 (dashed black) and HadSST3 (solid black, with shading for the 90% range of the 100 realizations) and from the all-forcing simulations with global SO_2 emissions (ALL; ensemble-mean (white) with grey shading for the 90% range of the 8-member ensemble) and without anthropogenic European (noEU; blue line and shading) and North American (noNA; red line and shading) emissions. In (b-c), differences between ALL and noEU (light blue line and shading) and ALL and noNA (orange line and shading) in area-averaged SSTs over (b) every but the North Atlantic and (c) the North Atlantic are shown. In (d-e), differences in the linear trends during 1850-1975 between ALL and (d) noEU and (e) noNA are shown, with stippling for significance at the 5% level and numbers in the top left corner for the fraction of stippled points within the displayed area.

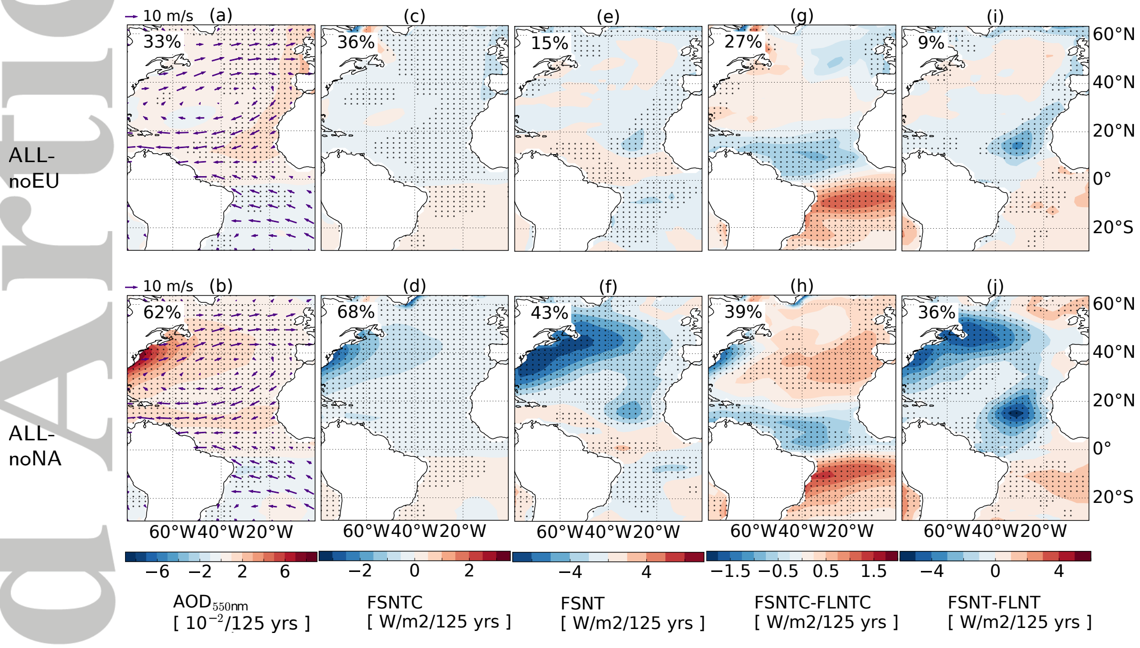

Figure 2. Simulated aerosol effects over the Atlantic: Linear trends as in Fig. 1(d-e), but for (a,b) AOD, and net (c,d) clear-sky short-wave (FSNTC), (e,f) all-sky short-wave (FSNT), (g,h) clear-sky total (FSNTC-FLNTC), and (i,j) all-sky total (FSNT-FLNT) radiation at the top of the model. In (a,b), purple arrows indicate the climatological wind near 850 hPa from the pre-industrial control run.

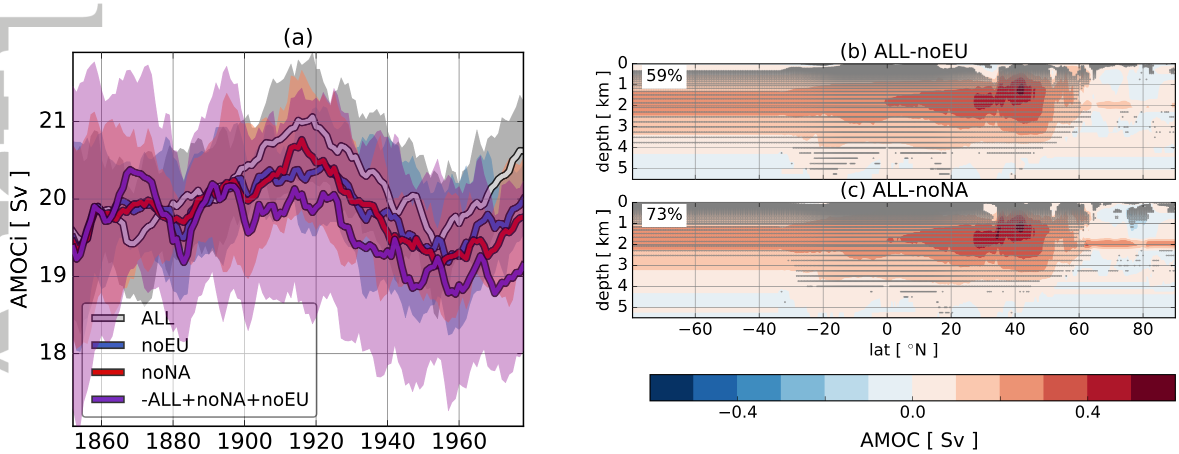

Figure 3. Simulated Atlantic Meridional Overturning Circulation (AMOC): (a) Annual-mean AMOC index (maximum AMOC at any depth) at 29.8°N. Colors and shading as in Fig. 1(a) except the AMOC response to the combined forcing of GHG, natural, and aerosols other than from NA and EU SO_2 emissions is also shown as approximated from arithmetically combining the ensemble-mean AMOC indices (purple). (b-c) Difference in the 1850-1979-mean AMOC between ALL and (b) noEU and (c) noNA. Stippling as in Fig. 1(d-e).

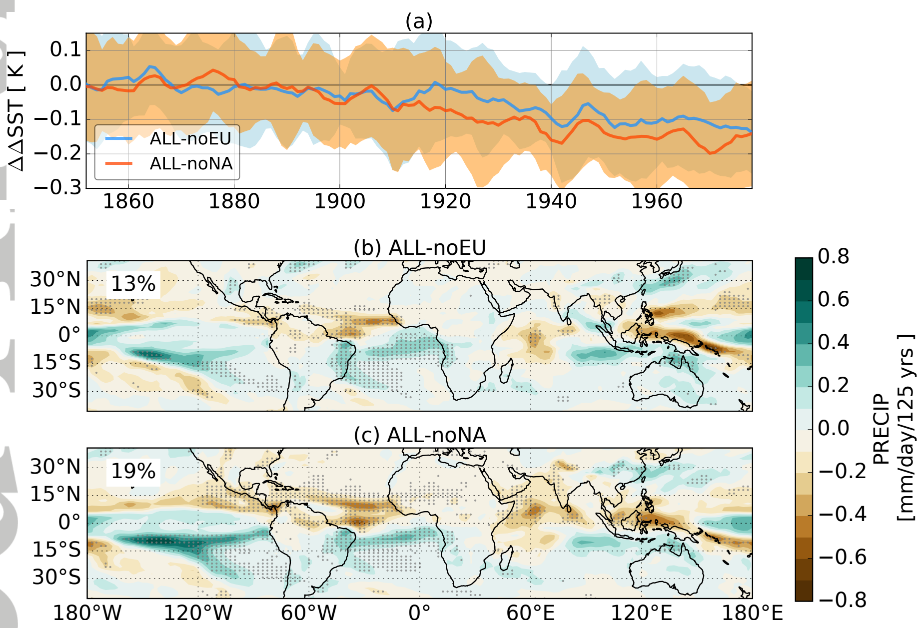

Figure 4. Simulated large-scale atmospheric circulation changes: (a) Time series of SST anomalies as in Figs. 1(a-b), but for inter-hemispheric SST difference, and (b-c) linear trends as in Fig. 1(d-e), but for precipitation.